PROBLEMS OF ORGANIC ADAPTATION[1]

LECTURE I

FITNESS IN THE LIVING WORLD

ADAPTABILITY may be defined as the power of self-regulation, self-preservation, and race perpetuation, by means of which living things are enabled not only to remain alive but also to adjust themselves to varied environmental conditions and to leave offspring. From the standpoint of any species the best that can happen is to increase and multiply, the worst is to become extinct. Self-preservation and race perpetuation are the *summum bonum;* everything that makes for these is beneficial and adaptive, everything that prevents or hinders these is injurious or unfit. Adaptability is a fundamental property of living things without which life itself could not long persist, for as Herbert Spencer has said, life is "continuous adjustment of internal relations to external relations." The origin of this or of any other fundamental property of life, such as metabolism, reproduction, or irritability, is shrouded in the same mystery as the origin of life itself.

On the other hand, adaptations are special adjustments to particular condi'tions; they are indvidual examples of the general property of adaptability. As such they have arisen in the course of organic evolution, and their origin, no less than other special structures and functions, must be explained by any adequate theory of evolution.

[1]A course of three public lectures delivered at the Rice Institute, March 8, 9, and 10, 1921, by Edwin Grant Conklin, Ph. D. (Johns Hopkins), Professor of Biology in Princeton University.

Such special adaptations to particular conditions of life are very common among all organisms, but they are not universal. Some organisms have been able to adjust themselves to one kind of environment and others to another kind, and although a certain degree of adaptability is universally present, no single organism is able to adjust itself to every kind of environment. Special adaptations to particular conditions of life are examples of differentiation, which always implies limitations in certain directions in order to progress in other directions. Consequently one organism is peculiarly fitted for one environment and another for another, but no organism is universally fitted for all environments.

Again, adaptations are relative but not absolute adjustments. Even the most perfect adaptation is not absolutely perfect. For example, that marvel of adaptation, the human eye, is very far from being a perfect optical instrument; Helmholtz is reported to have said that if an optician should send him an optical instrument as imperfect as the human eye, he would send it back to him and tell him to learn his business; and yet there is probably no more perfect adaptation in nature than this. Furthermore, all gradations of adjustment occur among different organisms from the relatively imperfect to the most perfect, and these gradations indicate that fitness in the living world is relative and not absolute, and they indicate that adaptations are a product of natural evolution rather than of supernatural creation.

Adaptations to particular conditions of life are seen in almost every structure, function, and relation of organisms; in the microscopic and ultra-microscopic parts of cells, as well as in entire cells, tissues, organs, systems, biological persons, and animal states; in the chemical and physical constitution and behavior of protoplasm and cells as well as in the morphological and physiological modifications which fit the organism to changed conditions of environment.

So general are such adaptations that it has often been asserted by naturalists and philosophers that they are universal—that all structures, functions, and relations of living things are adaptive or useful, or at least that they were adaptive at the time of their origin, and that, with regard to every vital process, we may properly ask the question, *cui bono*, being confident that it is or has been useful. This postulate of universal utility in the living world could be maintained only by assuming that many things which are now injurious had once been useful, and that many things which now seem to be useless will sometime be found to have a use. Such a postulate may be logically and hypothetically possible, but it is very improbable. While there are innumerable instances of utility in the living world, there are thousands of cases where structures, functions, or relations are in all probabilities not useful but indifferent, and some cases, though relatively few, in which they are positively injurious. Therefore it is not possible to maintain the postulate of universal utility in the living world.

Having found that general adaptability is universal in the living world but that success in making adaptations to particular conditions is never perfect and is sometimes lacking altogether, and that it is not safe to assume that every structure, function, or relation of organisms confers some known or unknown benefit upon its possessor, we may proceed to examine in detail some of the more striking and wonderful fitnesses which are found in the living world.

In this survey, we shall deal not only with the general relations of organisms to their environments but also with the intimate and minute adaptations found in organs, tissues, and cells, and we shall consider first, inherited adaptations, and later, acquired ones.

Our object is not to catalogue and describe the multitudes of adaptations which have been observed among animals and plants, but rather to find an explanation of their origin. However, since some recent writers have adopted the method of explaining adaptations by explaining them away and have solved the problem of their origin by denying their existence, it seems advisable to review some of the more striking fitnesses that are found among living things and especially among animals.

Let us begin by freely admitting that under the influence of the doctrine of supernatural design there has been a marked tendency to exaggerate the frequency and the perfection of organic adaptations. Many naturalists have seen adaptations where they do not exist and have invented environmental conditions to fit these fanciful adaptations, and when the usefulness of any structure or function could not be made probable even by these means, it was always possible to assume that this was due merely to our ignorance of the real functions of the part in question or the real needs of the organism. Sometimes the purely mechanistic results of necessary physical, chemical, and biological conditions have been regarded as special adaptations, and in general, the attitude of those who are looking everywhere for adaptations has not been very critical.

But when we are assured by some modern critics that all adaptations can be explained away in this manner, is it not evident that extravagant and uncritical opinion has swung to the other extreme? Adaptations may not be universal, they may not be perfect, but that they are very numerous and frequently so delicately adjusted to needs as to excite the admiration of the thoughtful, let the following classification and illustrative examples testify:

I. Racial or Inherited Adaptations

Inherited adaptations are those which appear in the development of individuals as if in anticipation of future needs and not as a result of present ones. The eye, for example, usually develops in the entire absence of light, and its various parts are formed as if in anticipation of their future uses; the same may be said of almost every other inherited adaptation. Particular adaptations characterize certain races, species and larger groups of organisms. Among these are innumerable structures, functions, habits, and instincts; indeed, one can think of scarcely any normal structure or function, reflex or instinct, that does not illustrate such racial or inherited adaptation.

1. The Efficiency of the Living Machine

This is an age of machinery, and the fitness of any machine is measured by its efficiency. Let us consider the fitness of the living machine as contrasted with those of human invention.

The frame or skeleton of most vertebrates is so constructed as to give the maximum of strength with the minimum of weight. Long ages before men had thought of using tubular frames in machines such as bicycles, nature had been using them in the shafts of long bones; ages before wire wheels and tangential spokes were thought of spicules and trabeculæ of bone were laced through the ends of long bones so as to afford maximum strength with minimum weight. Long before any human being had discovered, used, or classified the different forms of levers, nature had been using them in the limbs of arthropods and vertebrates.

The mechanical principles of the wheel and the screw are not found anywhere among organisms for the obvious reason that every portion of the animal machine must be connected by blood vessels and nerves with the central part, but the use by animals of levers of all kinds and for every conceivable purpose has never been surpassed in machines of human invention.

The motive power of the living machine is found in protoplasmic contractility whether it manifests itself in amœboid, ciliary, or muscular movement. But since all movement of large bodies must be brought about by muscles, we may limit our consideration to this type of movement. In spite of the fact that more attention has probably been devoted to the structure and function of muscle than to any other animal tissue, the ultimate causes of muscular contraction are still problematical. Nothing comparable to this form of motion exists except among animals. It is known that the chief source of chemical energy in muscular contractility is the burning of dextrose, but the manner in which this chemical energy is transformed into mechanical energy is unknown. However, the relative efficiency of different types of engines is known, and they may fairly well be compared with the living engine. The ordinary steam engine transforms about 10% of the energy of the steam into motion; the steam turbine, about 17%; the Diessel internal combustion engine has a practical efficiency of about 30%, while muscle has a net efficiency of from 20% to 30%. The living engine is therefore more efficient than the steam engine and about as efficient as the best type of engine that has been devised by man. But in addition to this, the temperature developed in muscle is much less, and the flexibility of the living machine, as measured by the rate or extent of movement, is much greater than in any other engine. For example, the temperature never exceeds 110° F. and is usually much less than this, while it reaches 5000° F. in a gas engine; the rate of contraction may vary from movements so slow as to be scarcely visible to a rapidity of about 24,000 contractions a minute, as in the beating of a mosquito's wings; the extent of movement may vary from a scarcely perceptible shortening to one one-hundredth part or less of the maximum expansion, as for example, in certain worms and in the tentacles of some cœlenterates.

Consider the variety, complexity, and efficiency of the means of locomotion in animals. Among the marvels of nature Solomon enumerates "The way of the serpent on the rock and the way of the eagle in the air," but the more usual forms of locomotion, such as running, jumping, climbing, digging, sailing, wading, and swimming show fitness and efficiency that are equally marvelous. Consider the manner in which unusual speed has been attained in the horse, giraffe, and antelope by the lengthening of legs and digits, the elevation of the animal upon the ends of the middle digits and the loss of the lateral ones. Consider the remarkable contrivances of the kangaroo, the jack-rabbit, the grasshopper, the flying squirrel for leaping; of the sloth, squirrel, and woodpecker for climbing; of the earthworm, mole cricket, and mole for burrowing. Among aquatic animals almost every means of propulsion which man has devised was discovered ages before by lower animals: the Portuguese man-of-war and the paper nautilus spread their purple sails to the breeze and "sail the uncharted main"; the jelly-fish and squid use hydraulic motors; fish, seals, and whales employ oars and sculls. Finally, consider the wonderful adaptations by means of which animals travel the highways of the air: the spider which spins a thread that floats out on the breeze and then, clinging to this gossamer, goes "ballooning" to new lands; the tremendous power of flight of the albatross and eagle; the apparently effortless soaring of the buzzard and frigate-bird; the flight of the arctic tern and golden plover from pole to pole, or the world-wide flight of the tiny humming-bird. Long ages before man had appeared on the earth, animals had conquered the land, the water, and the air; and although by means of his machines man can now surpass them in speed and strength in these three elements, they can still teach us much in skill and efficiency of locomotion.

The heart, with its valves, is a remarkably efficient pump; the strength and thickness of the muscular walls of the auricles and ventricles are nicely adjusted to the "load"; the valves are ideally constructed for quick, simple, and efficient action; the sequence of the beats in auricles and ventricles is usually perfect. Even more remarkable are adaptations to increased "load" during violent exercise or in high altitudes. In man the resting heart pumps about five pints of blood a minute, but in violent exercise it pumps seven times as much as this. The structures of arteries, veins, and capillaries are admirably suited to the needs of efficient circulation, and the mechanism for regulating blood pressure is extraordinarily efficient.

The efficiency of the living machine in the production of light, as for example in the firefly and glowworm, is incomparably greater than in the case of any lighting system of human invention. In electric lighting from 90 to 95% of the energy is wasted in heat and only 5 to 10% produces light, whereas these proportions are reversed in living things.

The mechanism for heat regulation in warm-blooded animals is wonderfully perfect. Irrespective of extreme changes in external temperature, the internal temperature is frequently maintained for years at a time within a few tenths of a degree. Anyone who has ever tried to maintain an incubator at constant temperature, and especially under great external changes, will be in a position to appreciate the remarkable efficiency of this living thermostat. In hibernating animals the body temperature falls during the winter sleep, and in severe weather it may continue to fall until it approaches the freezing point. The animal then wakes up, as if an automatic alarm had been set to rouse it when the danger point had been reached, and by means of muscular movements, increased respiration and oxidation, and sometimes by feeding, the temperature is raised. This safety device is found not merely in the highest warm-blooded animals, such as hibernating bears, but also among some insects, such as bees. When the temperature in the winter cluster of bees goes below 57° F. the bees become active, eat honey, oxidation increases and the temperature of the cluster rises.

The respiratory mechanisms by which oxygen is brought into contact with every particle of living substance and the exhaust gas is eliminated are far more perfect than is to be found in any other engine. In the case of insects, minute air tubes or tracheæ run to every part of the body, whereas in many other animals in which respiratory organs (gills or lungs) are limited to certain regions, the blood contains a substance, hæmoglobin, which serves as a wonderfully efficient oxygen carrier.

The mechanisms of living things for obtaining, preparing, absorbing, and utilizing substances as fuel are incomparably more complex and efficient than in any engine of human devising, and the utilization of foods for growth and repair is wholly unparalleled in any other mechanism.

The uniqueness of the living machine is nowhere more evident than in its capacity for reproduction. Imagine any machine of human invention which had the power not only to do the work for which it was devised but also to give rise indefinitely to other machines of the same sort! Nothing could illustrate more clearly the fundamental difference between the living and the lifeless machine than this power of reproduction. If reproduction is one of the fundamental and original properties of living things and is therefore not to be explained as a result of organic evolution, at least the innumerable adaptations for promoting reproduction have arisen in the course of evolution and demand an explanation. Among these are the differentiations of male and female sex cells and all the differences in structure, functions, and instincts between males and females; the remarkable contrivances for insuring cross fertilization in plants and animals and for preventing hybridization of species; the infinite variety and nicety of the means for the protection and nourishment of the young. Nothing in the whole world of living things is more wonderful than these adaptations for reproduction.

Consider the wonderful fitness of the nervous system for receiving and transmitting stimuli and for coördinating the multitudinous activities of animals. The timer of an automobile is no more perfect than the timing of the various contractions in the heart beat, and the timing of various muscular contractions in standing or walking and much more in talking or in playing any game such as tennis or baseball is vastly more complex and perfect than in any lifeless machine. Think of the fitness of every organ for its particular use and then consider the peculiar fitness with which these organs are coördinated into an harmonious whole.

Think of the variety and range of sensations in any higher animal and the admirable fitness of the sense organs: the fitness of the organs of touch and taste and smell, and the complex fitnesses and coadaptations of the many parts of the ear and eye. Many instruments of human invention are more sensitive to particular kinds of stimuli than some of the sense organs. For example, a thermometer is more sensitive to temperature changes than our heat and cold organs, the photographic plate is more sensitive to light than the retina, the microphone more sensitive to vibration than the ear; but when one considers the range and variety of stimuli to which higher animals are sensitive, there is no doubt that their sense organs are much more efficient than any non-living mechanism.

Finally, consider the durability of the living organism and its power of self-regulation and self-repair as compared with any other machine. Not for one moment between birth and death does the living engine stop. The heart and respiratory muscles cannot rest for a minute at a time during the whole course of life. Engines have been built that would run for a month or two without stopping for repairs, but the heart may continue to beat without interruption every second for a hundred years, pumping during this time not less than sixty million gallons of blood. The regulatory power of an organism is incomparably more varied and perfect than in any other mechanism; not only do all the complex processes of life occur, under normal conditions, in the best possible sequence and to the most favorable extent, but when as the result of abnormal conditions these processes are disturbed, the living machine has a wholly unparalleled capacity of regulation and restoration. When the living machine undergoes wear, injury, or loses parts, it is able to a surprising extent to repair itself and to restore or compensate for lost parts. What other kind of machine has a regulatory power that is comparable with that of a living thing?

When we consider the wonderful efficiency of the living machine in all of the respects named, is it any wonder that there have always been those who have refused to believe that it is really or only a machine? Is it any wonder that they have insisted that it must be controlled by some sort of indwelling intelligence? When we consider these remarkable characteristics, we may well say in wonder and admiration, "What a piece of work is a man!" or any other organism.

Such adaptations to general conditions of existence are so common that to most persons they do not seem remarkable, while some peculiar adaptation, such as the leaf-insect or the Venus fly-trap, seems wonderful simply because it is not common. Many of these more uncommon adaptations have played an important part in the discussion of the various theories of evolution which have been advanced during the past century. As illustrations of adaptations to peculiar conditions of life may be mentioned the fitness of horses' limbs for running, those of seals for swimming, those of birds for flight; or the adaptation of the long neck and fore legs of the giraffe to its habit of browsing on trees; of the long necks and legs of wading birds to their peculiar habits; of the small fore legs and large hind legs and tail of the kangaroo to its peculiar method of locomotion. In this connection must also be considered the absence of limbs in certain lizards, snakes, and amphibians, and the degeneration or loss of wings in the apteryx and dinornis among birds and in certain insects inhabiting stormy islands. Here also must be classed the cases of adaptive atrophy or hypertrophy of organs, as for example the loss of eyes by cave animals, the decreased size of the jaws and teeth of civilized man as compared with savages, the increased size and length of the middle digit, and the reduction or disappearance of the lateral digits in ungulates, etc.

2. *Adaptations for Defense and Offense*

Every principle of defense known and used by man has been employed by lower animals for uncounted millions of years. Among these are thorns, spines, and armor, camouflage, the false flag, and that most effective means of defense —a strong offense. Thorns and spines, frequently barbed and poisonous, are of wide occurrence among animals and plants. The cactus and bramble, the sea-urchin and porcupine, ward off enemies by their bristling surfaces. Mollusks, crustacea, armored fishes, dinosaurs, tortoises and armadillos are veritable armored cruisers or land tanks.

Nowhere has the principle of camouflage been carried to such extent or perfection as among certain animals. The principle of protective coloration is of very general occurrence in the animal world. The polar bear and fox, the lion and antelope, the dark upper and light under surfaces of birds, resemble the backgrounds against which they are usually seen. Even the tiger and zebra are protectively colored to match the lights and shades of their natural habitats, a thing which can be readily believed by anyone who has seen the bizarre bars and patterns on camouflaged ships. When the background changes, as from winter to summer, some animals change their colors, as in the case of the ptarmigan and arctic hare, which are white in winter and gray or brown in summer. Other animals change colors and patterns very rapidly to match corresponding changes of the background, as in the case of cephalopods and fishes (especially flounders), amphibians and reptiles (notably chameleons).

Animal camouflage includes not only colors and color patterns, like those of the background against which the animal is seen, but also shapes and outlines like those of surrounding objects. Some fishes, crustaceans, mollusks, and worms which live in sea-weed are covered with streamers, and ragged processes so like sea-weed that it is very difficult to distinguish them from the weed. Certain animals, such as the stick insect, dead-leaf butterfly, and bark spider are so much like the objects on which they are commonly found, both in form and color, that it is difficult to detect them even when searching for them. Other common forms of camouflage are found in "feigning death," or rather in remaining perfectly quiet to escape detection, for moving objects even though they have concealing colors or forms are much more readily seen than those that remain motionless.

The use of a "false flag," which has been so much condemned in human warfare, has apparently been resorted to by animals in certain instances. Such sailing under false colors is known in zoölogy as "mimicry." Insects that are protected by nauseous odors or by other means are sometimes mimicked in form, color, and peculiarities of posture or locomotion by other insects not closely allied to them. Snakes that are non-poisonous sometimes mimic poisonous ones in forms, colors and threatening attitudes. But in zoölogy it is almost as difficult to establish the use of a false flag as it is in naval warfare, and it may be that two different species have independently developed similar flags so that neither is "mimic" or "mimicked."

Electrical fishes, such as the electric eel and the torpedo, are able to generate a strong charge of electricity with which they can shock and stun their enemies or their prey. Of course submarines and flying machines are an old story in animal life, and even smoke screens, or what correspond to these, are used by the squid and other cephalopods which in fleeing from enemies throw out a cloud of ink which conceals them. These modern methods of human warfare have been used for millions and even hundreds of millions of years by lower animals.

In animal, as well as in human warfare, the most effective defense is a strong offense, and innumerable adaptations are found for this purpose. Among these are many ferocious modifications of teeth, such as tusks, sabers, and swords; great developments of spurs, claws, pincers, and horns; poisons and poison gases, such as the sting of the bee, the poison of serpents and scorpions, the odors of bugs and skunks. These last anticipate in many respects some of the newest methods of gas warfare. But although many animals have stings and spears, none has developed projectiles that can be discharged at a distant mark.

When one considers all these striking contrivances for defense and offense, together with the appropriate behavior by which they are accompanied, such as the well-known habits of the rattlesnake, the porcupine, the opossum and the skunk, the question inevitably arises whether lower organisms have not discovered these means of protection in a manner comparable to the way in which man has discovered methods of defense and offense.

3. Interorganismal Relations

Another class of racial adaptations is found in certain typical correlations between animals and plants, between different species of animals or plants, and between different individuals of the same species. Fifty-six years before Charles Darwin published the "Origin of Species," Konrad Sprengel (1793) published a work entitled "Das neue entdeckte Geheimniss der Natur" in which he proved that flowers exist for the purpose of attracting insects in order that the insects may carry pollen from flower to flower, thus insuring cross fertilization. The contrivances by which flowers attract insects, such as color, scent, and nectaries, reach a climax in such plants as orchids, in which the nectary can be reached only by a particular route and by certain species of insects, and the pollen is so located in the flower that masses of it will become attached to the proboscis or other portions of the insect, and these masses will then be deposited upon other flowers of this species visited by the insect. Both flowers and insects are benefited by this adaptive relationship. The yucca moth collects pollen from one flower of the yucca, flies to another flower and lays her eggs among the ovules, and then places pollen upon the stigma, without which fertilizing act the ovules would not develop. As the larvæ of the moth develop, they eat a part of the ovules but leave a part, so that seed is produced, and thus both species are perpetuated. This act is performed but once in the life of a moth, so that there is no opportunity of learning by experience or imitation. It is a principle in such mutual dependence that each member must conserve the other, and even in parasitism the parasite must not usually destroy the host else it will at the same time destroy itself.

Extraordinary cases of adaptation are found in the peculiar life histories of certain parasites, which must pass through one or more larval stages in intermediate hosts before they reach the adult stage in the final host. Consider, for example, the almost infernal ingenuity shown in the life history of the malarial organism, which adapts it to life in the mosquito and in man and to its transfer from one to the other; or the adaptations shown in the life history of the liver-fluke, which passes through four different larval stages in one or two intermediate hosts before reaching its final host; or the life histories of the tapeworm or hookworm or trichina, which are wonderfully adapted to securing the survival, multiplication, and distribution of these parasites. Perhaps nothing in nature exceeds in complexity and nicety of adaptation the life histories of such parasites.

The more common relationships of individuals of the same species, as for example between males and females, parents and offspring, and all the castes with their different functions among social insects, are notable instances of adaptation. What is more wonderful than the great drama of sex, in which all living things, except the very lowest plants (bacteria), are actors, in which admirable coadaptations for bringing about cross fertilization are found, all the way from the structures and functions of the egg and spermatozoon to the secondary sexual characters and the complicated instincts and behavior of males and females? Consider the very common adaptations found in the relations of parents and offspring, the various methods by which the young are protected and supplied with food, and the complicated behavior which characterizes this relationship in higher animals.

4. Adaptations of Development

To the embryologist at least, no adaptations are more striking than those of development. In the normal development of an egg or embryo every step leads to what seems to be a preconceived end. The differentiations of ontogeny are usually adaptive. The cleavage of the egg subdivides the egg substance both quantitatively and qualitatively in such manner as to determine the relative sizes and locations of future parts. Even the distribution of substances in the unsegmented egg may foreshadow the proportions and localizations of future organs. These organs develop not for immediate but for future uses and in anticipation of distant needs. For example, consider the development of the eye; the retina with its sensory rods and cones, the lens with the ciliary processes and muscles for focusing, the transparent cornea and humor—each and every portion of the organ develops toward the end, or shall we say "for the purpose," of vision, and yet there is no vision until after all these parts are formed and connections have been made with the central nervous system, which does not occur until late in development, sometimes, as in the case of the rat, some time after birth. Organs are sometimes developed which are used only once in the life of the individual, as, for example, the egg-tooth on the beak of a bird, which is used only for breaking its way out of the shell at hatching.

In all of its general features development is teleological, and contemplating this we may well appreciate the words of the psalmist, "I am fearfully and wonderfully made." "In thy book all my members were written which in continuance were fashioned when as yet there was none of them."

5. *Adaptive Behavior*

Some of the most striking of all adaptations are found in the field of behavior and instincts. Even the simplest plants and animals avoid injurious regions and substances and find beneficial ones. For example, some bacteria will aggregate in certain regions of the spectrum and avoid other regions; they move away from salt solutions, or from distilled water, and collect in nutritive substances. Paramecium and many other protozoa behave toward injurious or beneficial substances in a similar manner, and especially notable is the way in which Paramecium avoids extremes of heat and cold and remains in regions of moderate temperature. The tropisms of germ-cells, of seeds, seedlings, and embryos, are generally adaptive. In plants as well as in animals the sperm finds the egg and is received by it. The root of the seedling grows down into the soil and the shoot up into the light and air. Sensitive plants close their leaves when stroked or exposed to dry air, thus preventing injury or dessication. Insectivorous plants catch insects by sticky secretions or traps, and they then infold and digest them. The plant known as "Venus fly-trap" does not respond, by closing, to a single stimulus, such as would be produced by accidental contact with a falling object, but only when the stimulus is repeated within three minutes, as it would be if that object were an insect; incidentally, this behavior shows that this plant has a kind of memory ("organic memory") which lasts for a period of about three minutes.

The behavior of higher plants and animals is almost always adaptive, and where it is not so it can usually be explained as the result of unnatural, or at least unusual, conditions; thus the tendency of insects to fly into a flame is the result of positive phototropism, which is beneficial in a state of nature and injurious only in the artificial conditions created by man. The behavior of insects is sometimes so remarkably adaptive that it seems to be intelligent and purposive. Thus the solitary wasp, *Sphex,* digs a burrow in the ground and stores it with caterpillars which have been stung in such a way as to paralyze but not to kill them. On these caterpillars she lays her eggs, and when the larvæ hatch they find an abundance of fresh meat for food. On leaving the burrow the mother *Sphex* carefully conceals it by closing it with earth; the Peckhams and more recently several others have observed that she then takes a small stone in her mandibles and pounds the earth down with it and then smooths the earth so that all traces of the burrow are removed. The instincts of ants and bees have long been studied, but they never lose their charm and interest; the instincts of the different castes or members of the colony, and even of the same individual at different stages of its life, are very unlike, and yet all are adapted to the preservation and prosperity of the colony.

The migratory habits of animals are no less wonderful. At the breeding season myriads of shad and salmon migrate from the sea far toward the sources of fresh-water streams where the young may grow up in comparative safety, and although very few of the adult animals ever get back to the sea, yet this same instinct for migration possesses every new generation as it did the old one. The immemorial migrations of certain birds, going north in spring and south in autumn, are equally wonderful. The value of such an instinct to the birds is easily understood; but how did it arise, what series of natural causes can explain such an instinct? These adaptive instincts are no exceptions but only striking illustrations of a universal phenomenon among organisms. How can such useful and apparently intelligent and purposive adaptations be explained? Are intelligence and purpose in man fundamentally different from this adaptive behavior of animals? Apparently many gradations exist between these two, and in the development of the human individual every intermediate step is found between mere tropisms at one extreme and intelligence at the other. If tropisms and instincts are generally adaptive, are not intelligence and purpose higher and more complicated forms of adaptation?

6. Cellular Adaptations

Adaptations are found not only in gross structures and functions but also in the most minute, not only in tissues and cells but also in the smallest parts of cells. For example, what is there in the whole world more remarkable than the complex mechanism of nuclear division? We now know that the material basis of heredity is located in certain portions of the nucleus, the chromosomes, and, if this material is to be equally distributed in development to all portions of the body, each chromosome must be divided with exact equality and the halves separated into the two daughter cells formed at each division. This "purpose" is accomplished by the complex mechanism of mitosis, which is almost universal in occurrence and has existed at least as long as many-celled animals and plants have, but which was not discovered by man until the middle of the nineteenth century, and its significance has been appreciated only during the past forty years.

Since chromosomes are persistent structures their number would double, and the inheritance material would double, every time a spermatozoon unites with an egg, were not some provision made to prevent this. Such provision is made in a unique form of nuclear division, which takes place only once in the whole life of an individual—in man once in billions of billions of divisions. This unique division is brought about by the union of corresponding or homologous chromosomes of the father and mother at the time of the formation of the germ-cells—a process known as synapsis—and the subsequent separation of these *whole* chromosomes in mitosis, so that each germ-cell, whether egg or sperm, contains only half the normal number; then when egg and sperm unite in fertilization, the normal number is restored. Upon these processes of synapsis and reduction of chromosomes and subsequent union of egg and sperm depend all the phenomena of Mendelian inheritance.

The fact that in most species males and females occur in equal numbers has always been regarded as a remarkable adaptation—indeed, the fact that males or females, with their coadapted structures, functions, and instincts, should occur at all is a notable adaptation. It is now known that sex is determined by a certain combination of chromosomes; in the female there are usually two sex chromosomes (xx), in the male there is only one (x), or a combination (xy). In the process of chromosome reduction at the time of the formation of the sex cells, each egg receives one *x* chromosome, while one half of the spermatozoa receives one *x* and the other half a *y* chromosome or none. If then an egg is fertilized by a sperm containing an *x*, a female is produced, but if fertilized by a sperm containing a *y* or no sex chromosome, a male is produced; and since these two types of spermatozoa exist in equal numbers it results by mere chance, on the theory of probabilities, that males and females are produced in equal numbers. But there is no evidence that this remarkable mechanism of sex determination is itself the result of mere chance, and, however it may have been caused, it is a wonderful example of adaptation.

The fertilization of an egg is a very complex process, and yet every step in that process is adaptive. An egg ready for fertilization gives off substances which activate the spermatozoa, and when by its active movements a sperm comes into contact with the egg, the latter sends out a process to receive the sperm. Immediately after this the whole surface of the egg undergoes some change which usually makes it impossible for another sperm to enter. If by any means more than one sperm nucleus unites with the egg nucleus, the resulting development is very abnormal. Thus the provision for preventing multiple fertilization and pathological development is highly adaptive. Many other cases of intracellular adaptations could be cited, but the ones mentioned indicate that adaptations are found in the smallest as well as in the largest parts and functions of organisms—"Natura in minimis maxima."

7. The Subtle Chemistry of Life

Although chemists no longer hold that there is a great gulf fixed between organic and inorganic chemistry, and although certain organic compounds can now be made artificially in the laboratory, every living thing performs many complicated chemical processes which the chemist can neither duplicate nor understand. In particular the power which all kinds of protoplasm have of converting food substances into their own peculiar kinds of protoplasm—the power of assimilation—is a chemical secret which the mind of man has not been able to discover, although every cell of his body knows this secret. The secret of "fixing" free nitrogen was discovered by some of the simplest bacteria hundreds of millions of years ago, and their efficiency in this respect is much greater than man can hope to attain either at Niagara Falls or Muscle Shoals. The ability of all green plants to convert water and carbon dioxide into sugar and starch in the presence of sunlight is a secret of such importance that if man could duplicate the process cheaply and efficiently it would forever solve the problem of the food supply. The chemical processes involved in fermentation and digestion may be artificially duplicated by man, but only with the aid of chemical substances known as enzymes, which are made by even the simplest kinds of protoplasm but which cannot be artificially produced by man.

Other substances known as chemical messengers, or hormones, which are produced by certain ductless glands and which circulate in the blood, profoundly influence the growth, development, and activity of many distant parts of the body—indeed, many of the most remarkable correlations of growth and form, of function and structure, of differentiation and integration, are determined by hormones. There is good reason to believe that they are the real materials of heredity, and that they determine race, sex, and type of personality; but although these hormones may be produced by chromosomes, cytoplasm, and glands, they cannot in general be synthesized by human intelligence. Other chemical substances of unknown composition but of the most vital importance as accessories to food are known as vitamins. They are produced only by certain cells and tissues of plants and animals, and they have never yet been analyzed or synthesized.

These are only a few of the many unique and wonderful chemical secrets which protoplasm has discovered but which are as yet largely beyond human comprehension. How did lowly plants and animals ever discover such subtle secrets of chemistry, which intelligent man is only coming to appreciate and which he cannot yet artificially duplicate?

II. Individual, Acquired, or Contingent Adaptations

As contrasted with such racial or inherited adaptations, there is a whole class of fitnesses which may be known as individual, acquired, or contingent. These are adaptations which arise in response to particular stimuli; they are not inherited, as the structure of the eye is, for example, which develops in the dark as well as in the light, and which is fully formed before it is put to the use for which it is fitted, but they are acquired in that they arise in each individual in response to particular external conditions, and they are contingent in that they may or may not appear, depending upon whether the appropriate stimulus is present or not.

Among these individual adaptations, or useful responses to stimuli, may be listed the following classes:

Stimulus	*Beneficial Response*
Increased light	Increased pigmentation
Increased friction	Increased thickness of epidermis
Increased use	Increased size or strength
Unusual foods	Appropriate digestive fluids

Stimulus—Continued	*Beneficial Response—Continued*
Unusual temperatures	Acclimatization
Poisons or toxins	Toleration or antitoxins
Injury	Regulation or regeneration

Strong light, and especially light of short wave lengths such as ultra-violet, is very injurious to protoplasm, and when the skin of white persons is exposed to such light the living cells suffer "sun-burn." But another result of such exposure is that the skin becomes more deeply pigmented or "tanned," and this screen of pigment serves to protect the living cells from the injurious rays.

Moderate friction and pressure on the skin, instead of wearing it thin, leads to the thickening of the epidermis and the formation of callosities by which the deeper lying parts are protected. A similar result follows the application of various chemicals to the skin. The epidermis of plants that are exposed to salt-water spray becomes thickened, thus protecting the protoplasm from the injurious effects of the salt.

It is a truism that in living things alone use strengthens a part and disuse weakens it. The used muscle grows in size and strength, and, within certain limits, it fits itself to the task required of it, while the unused muscle grows small and weak. A similar thing is true of glands, and even sense organs or brains may be improved by use.

Unusual kinds of food often lead to adaptive modifications of the digestive organs. Grain-eating birds have a tough gizzard with a hard lining, but if they are fed on soft foods the gizzard becomes soft and flabby. If animals which live largely on meat are put upon a carbohydrate diet, or *vice versa,* the character of the digestive fluids undergoes an appropriate change.

Remarkable also are the adaptations which many organisms show to extremes of temperature and to dessication. By gradually increasing the temperature of the water certain protozoa have been acclimatized to water so hot that other individuals of the same species that have not been so acclimatized are instantly killed and cooked when placed in it. Some animals and plants may undergo complete dessication and yet come out "as good as new" when they are again placed in water. There is a small rotifer that is found in rain gutters and cemetery urns which can be completely dried so that it contains no trace of water. When it is again placed in water, it is not only completely restored, but is found to have renewed its youth.

Even more remarkable are the adaptations that organisms show to certain poisons, if these poisons are given in graded doses so that the organism acquires a tolerance for them. Such tolerance may be acquired to a limited extent to violent mineral poisons, such as corrosive sublimate, as Davenport showed in the case of Paramecium. It is also known that human beings, as well as other organisms, may acquire tolerance for arsenic and arsenical compounds. One such compound is "salvarsan," and Ehrlich, its inventor, points out the importance of giving it in doses large enough to kill the syphilis organism "mit einem Schlag," since the organism will acquire a tolerance for the poison if it is given in smaller doses. But the poisons to which living things most readily become adapted are those of organic origin, such as alkaloids. It is well known that "drug fiends" may take enough morphine or cocain to kill a man, who is unaccustomed to the drug, without any very serious or immediate injury. Similarly, tolerance is gradually acquired for tobacco, alcohol and many other poisons. Among the most striking instances of this is the tolerance to serpent's venom and to bacterial toxins. If the venom of rattlesnakes or cobras is injected into guinea-pigs or rabbits in graded doses, they may be rendered immune to the poison even when given in lethal quantities. The venom of every poisonous snake is highly specific, and the antidote for one kind of venom will not serve as an antidote for another kind. Furthermore, it is certain that the ancestors of the guinea-pig, which is a native of South America, could never have had any experience with the venom of the cobra, a native of India; and yet the guinea-pig can form an anti-body against cobra venom, and for every particular kind of venom its own peculiar anti-body. One who has had diphtheria has acquired a toleration for the diphtheria toxin, so that he is thereafter usually immune to that disease. In this way most persons have acquired immunity to certain common diseases. It is known that each kind of toxin leads to the formation of a specific anti-body which serves as an antidote for that poison. Many of these toxins are complex and highly specific substances, and yet the living organism, if given sufficient time, can make a specific antidote for each particular kind of toxin. What chemist by the use of his intelligence could do anything approaching what his unconscious cells are able to do in this respect?

Internal regulation is frequently the result of the action of certain internal secretions, or hormones. Thus the ability to "nerve oneself" for a great effort involves many correlated adjustments, such as increase of heart beat, of blood pressure, of respiration, and of muscular energy, and all of these are caused by setting free into the blood "adrenin," which is secreted by the adrenal gland; even the coagulability of the blood is increased by this hormone. The adaptive character of all these reactions can be readily appreciated when it is realized that these are just the conditions needed in fight or flight, and in life and death struggles. It is probable that many regulations of development are dependent upon a proper sequence and balance of internal secretions. Such a secretion known as "andrase," formed by the interstitial cells of the testes, leads to the development of the secondary sexual characters of the male in mammals, while a corresponding hormone, known as "gynase," is formed by the ovary and causes the development of the secondary sexual characters of the female. The great changes which accompany pregnancy and lactation in mammals are caused by hormones from the ovary and the fœtus. Other internal regulations affecting many parts of the body and the general course of development are caused by hormones from the thyroid gland, the pituitary body and many other organs of internal secretion.

But although the hormone is the chemical stimulus which leads to the adaptive reactions in each of these cases, it does not in the least explain the fact that these reactions are adaptive. Why should the reactions of so many different organs to adrenin be of such a nature that they coöperate to fit the animal for fight or flight? Why should the reactions of so many different parts of the body to andrase or gynase be of such a character that they lead to the development of all the complicated organization of the male or female, and why should the organization of the two sexes be so adapted to each other? It is evident that the stimulus which starts these adaptive reactions does not explain the fact that they are adaptive. That can be found only in the teleological nature of the mechanism which is set in motion by these hormones.

Finally, some of the most remarkable of all individual adaptations are found in the regulations and regenerations which follow injury. Many eggs, embryos, and adults have the power of restoring lost parts and in general of resuming their typical form after injury. Certain flat worms and hydroids may be cut up into minute fragments and each piece will give rise to a typical animal. Some eggs may be broken apart in the two-cell or four-cell stages and each cell will give rise to a whole individual. Many lower animals such as newts, crayfish, and worms have this power to a very marked degree. The legs of a newt or crayfish may be cut off again and again and yet may be replaced after each amputation. In the regeneration of the legs of crabs, Morgan has shown that those legs which are least liable to injury regenerate as readily as those which are most liable to be lost. If the lens in the eye of a newt is removed, it will regenerate more or less perfectly. Such individual adaptations cannot be explained as the result of the inherited experiences of former generations, since the injuries are frequently of such a kind that they could never have occurred in nature.

Higher animals do not have such extensive power of regeneration, but every living thing has this power to a certain extent. Human beings cannot regenerate limbs or other complex parts, but they have the power of healing wounds and making repairs, otherwise cuts and other little injuries would prove fatal.

These individual adaptations are only samples of innumerable others that could be cited; indeed, individual adaptations are almost if not quite as numerous as racial ones, and they are even more mysterious and wonderful, since nothing in the world seems more inexplicable than the ability of an organism to respond in a useful and apparently purposive way to conditions which it has never experienced before and which in some instances even its ancestors could never have experienced in all their past history.